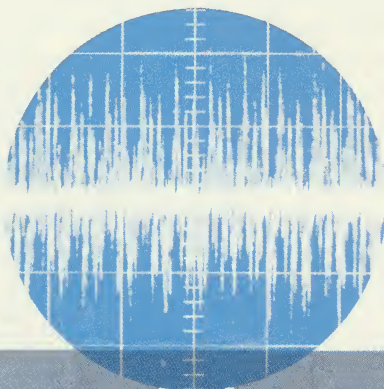


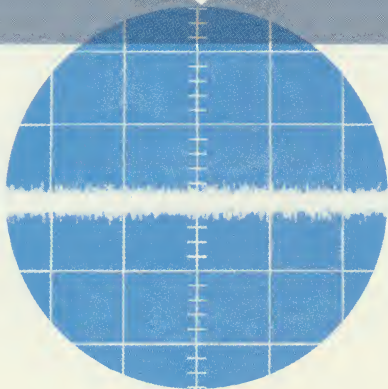
the **EMUR** *telemeter*

NUMBER 6

APRIL, 1967



TAPE SPEED COMPENSATION



Tape Recorders in Telemetry Systems

The use of tape recorders in telemetry data-processing systems is increasing as the handling of data in real time becomes more difficult. This is due, in part, to the limited availability of rf links in airborne applications and to the increase in the number of telemetered data points and detailed data evaluations. But along with its usefulness and versatility, the instrumentation recorder has several drawbacks which adversely affect system performance.

One recorder problem area is the tape transport system which must move the tape past the heads at a constant velocity to maintain data accuracy. Random speed variations result in unwanted frequency modulation of the signal in FM systems and introduce timing errors, or pulse jitter. This can be a major problem in time-multiplex systems and others where correct timing is essential.

However, tape speed compensation (TSC) circuits are available to improve system performance substantially. The basic principle of TSC is to record a stable reference frequency with the data, detect the recorder-induced errors from the reference, and then use the error signal as a feedback control to cancel out the original effect. This article explains the effects of recorder speed errors in telemetry systems and shows how large improvement ratios are realized by using TSC in the recorder motor circuit and the multiplex/demultiplex electronics.

Recorder-Induced Errors

The major limitation of the tape recorders used in telemetry systems is mechanical rather than electrical/electronic. The tape transport system, the heads, and the tape itself are larger error-inducing elements than the associated electronics. These elements produce complex time-base and frequency errors which may not be acceptable in certain applications, even though the errors are reduced to a small value in many modern recorders. Two such applications are airborne recorders and telemetry systems using untranslated constant bandwidth channels with low deviation percentages. Airborne recorders present a problem since they are usually a compromise between performance characteristics and mechanical design. The susceptibility of certain constant bandwidth channels to recorder-induced errors is explained later in this article.

Mechanically caused errors in tape recorders vary in terminology and definition from one reference source to another. The basic and more common terms are discussed here only as background data. Detailed descriptions and test setups regarding tape recorder errors are included in the **IRIG Telemetry Standards**, Document 106-66.

Multiple-speed recorders provide the engineer with the advantage of flexible evaluation. For example, if a 5000 Hz tone is recorded at 30 inches per second (ips) and played back at 60 ips, the tone will be increased to 10,000 Hz and the playback time is halved.

Similarly, if two pulses spaced 1 μ sec apart are recorded at 30 ips and played back at 60 ips, the time base is halved and the pulses will appear to be only 0.5 μ sec apart. This feature permits data speed-up or slow-down during the record or playback mode of operation.

As long as the speed change is a known factor and remains constant within a speed range, a true evaluation of the data can be made. However, small random speed changes

introduce errors which, through misinterpretation, could result in a false conclusion. For example, a recorded FM signal increases in frequency with an increase in tape speed and decreases in frequency with a decrease in tape speed. Errors caused by poor speed regulation are shown in Figure 1. They can be classed in two broad categories according to the type of data being recorded; frequency errors in FM systems, and time-base errors in pulse systems.

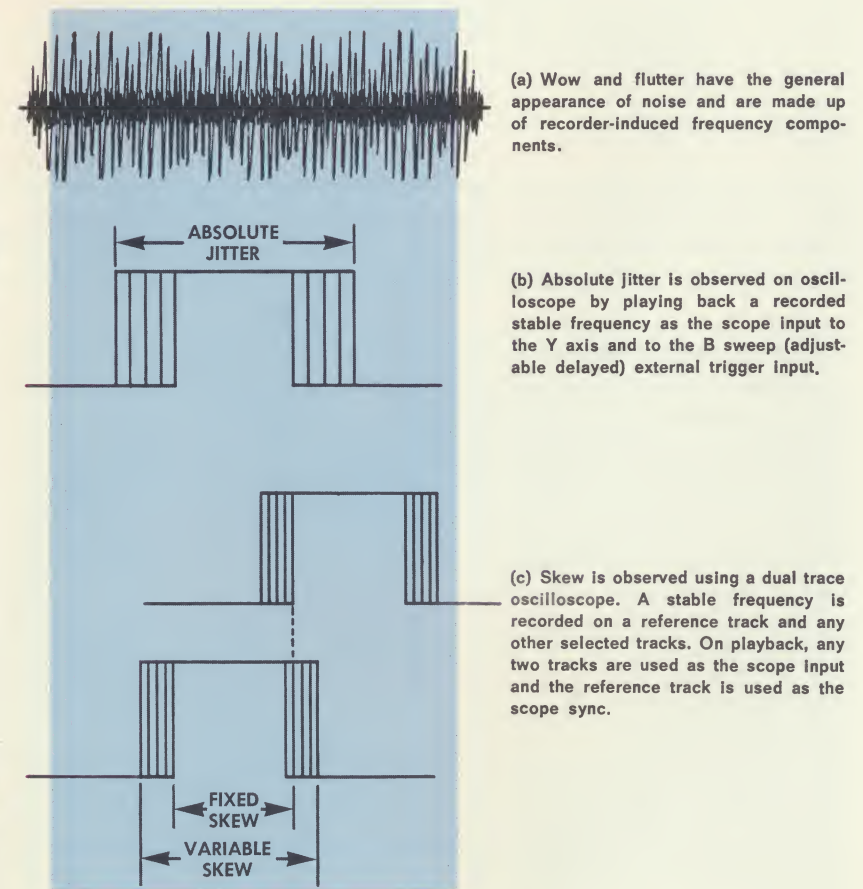


FIGURE 1. Recorder-Induced Variations

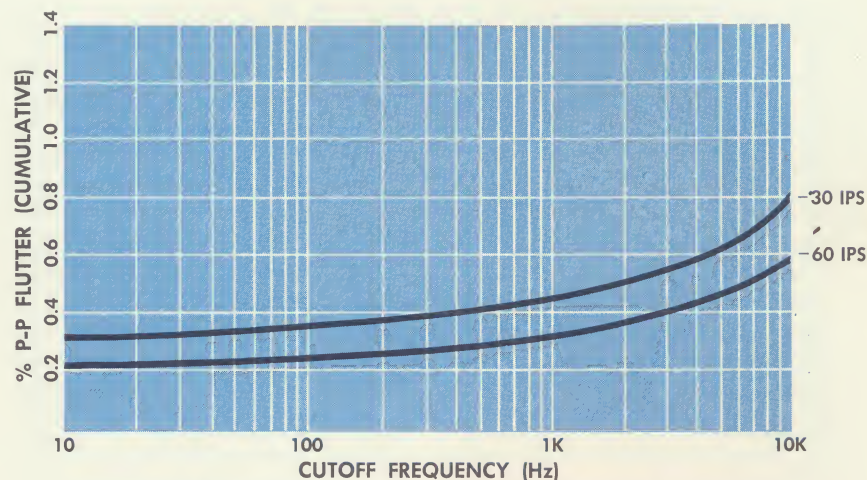


FIGURE 2. Cumulative curves show that flutter components are lower at higher tape speeds. Curves are the result of numerous plots of P-P values measured at half octaves with the aid of sharp cutoff filters.

Tape Error Definitions

The following terms and definitions are in general use in the audio industry where frequency recordings have been used for some time.

Drift: Tape Speed variations at frequencies below 0.1 Hz.

Wow: Tape speed variations at frequencies between 0.1 and 10 Hz.

Flutter: Tape speed variations at frequencies above 10 Hz.

However, since these terms resulted from their effects on the human ear, they are not widely used in the instrumentation field to identify such discrete frequency ranges. Instead, instrumentation specifications tend to combine the several terms into wow and flutter. In most cases, the terms are simply referred to as flutter with the frequency range of interest noted directly, usually by the bandwidth measurement.

Flutter magnitude is given as a percentage in peak value, peak-to-

peak value, or rms value. It can be expressed directly as the variation from the nominal speed or indirectly as the frequency variation. Peak and peak-to-peak values provide the instrumentation engineer with more descriptive data than an rms reading. Peak-to-peak flutter in terms of frequency variation is given by:

$$\% \text{ Peak-to-peak flutter} = \frac{f_{\text{max. carr.}} - f_{\text{min. carr.}}}{f_c \text{ carr.}} \times 100$$

If a 56,000 Hz tone is recorded and the frequency spectrum on playback varies from 55,700 to 56,300 Hz, the flutter content is 1.07% peak-to-peak. Peak-to-peak flutter in terms of magnitude can be measured at the output of an FM detector by any peak-to-peak indicating device such as an oscilloscope. To be meaningful, a flutter specification should therefore indicate the bandwidth of measurement, the tape speed, and whether it is peak, peak-to-peak, or rms. As a comparison, wow and

flutter (speed errors) may vary from as little as $\pm 0.1\%$ for sophisticated laboratory recorders to as high as $\pm 7\%$ (with $\pm 3\%$ being typical) for airborne recorders.

A typical set of flutter curves is shown in Figure 2. A stable single frequency is recorded and variations in the reproduced signal are analyzed and plotted using sharp cutoff filters to determine the peak-to-peak value in a cumulative manner, starting at the lowest frequency and increasing in half-octaves to the highest frequency of interest. Analysis is accomplished using an FM demodulator and oscilloscope calibrated for a selected deflection at a given (known) frequency deviation. Using this point as a comparison reference, the percent peak-to-peak flutter can be determined for the various plot points in the graph. Flutter components exist

throughout the interested bandwidth of measurement (usually given as 0 to 10 kHz in recorder specifications), have the general appearance of noise, and decrease as the speed of the recorder is increased.

Speed variation of the tape transport results in **skew** and **time-displacement errors** of recorded pulses. Skew, also called inter-channel time displacement error, is a variation in playback of pulses recorded at the same time on different tracks. Fixed, or **static**, skew can be caused by electronics, head azimuth misalignment, and uneven tape movement as shown in Figure 3. Most variable, or **dynamic**, skew is induced by dimensional instability of the tape and slitting inaccuracies incurred when cutting the tape to operational widths. As a matter of economics, tape is usually manufactured in wide rolls

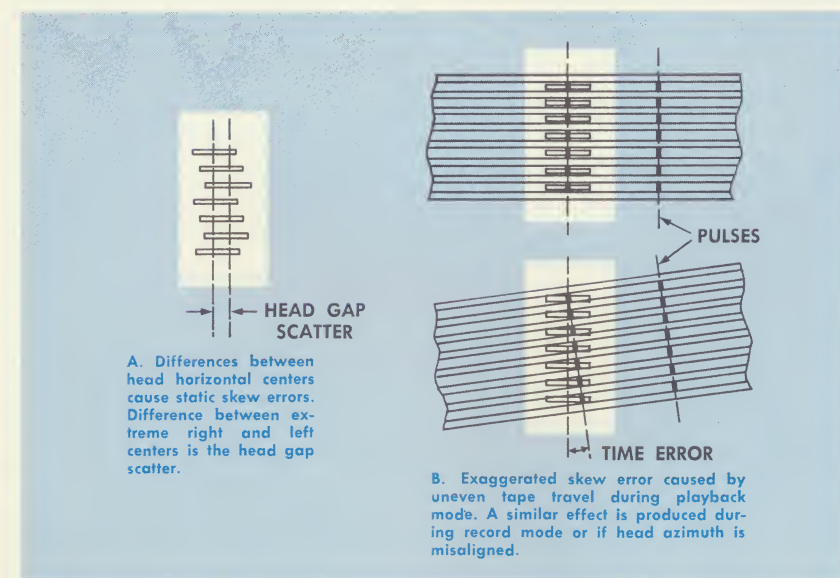


FIGURE 3. Mechanical make-up and alignment of recorder heads are responsible for fixed (static) skew errors.

which also enables the magnetic coating to be applied in a consistent thickness. Time displacement error, also called time-base error or **jitter**, is the variation in playback of two or more pulses recorded on the same track. Jitter is a function of the integrated value of the flutter over the period of time between pulses, and it depends on flutter frequency and time lapse between pulses.

Some tape recorders exhibit a dynamic time base distortion due to a scraping action between the heads and the tape, sometimes referred to as **stiction**. These recorders have an open-loop drive system which has an unsupported loop of tape between the reproduce head and the capstan. This loop represents a distributed mass under tension which has its own natural period of vibration. The longitudinal vibrations produce a "violin-string" effect at the resonant frequency of the loop, usually between 2000 and 3000 Hz. This effect is greatly reduced in a closed-loop system where pinch rollers are used to shorten the length of unsupported tape and provide mechanical isolation. The more elaborate laboratory recorders use vacuum chambers to provide the required support and isolation.

Effects of Tape Speed Errors

The effect of these errors on a telemetry system can be expressed in terms of signal-to-noise ratio or error in percent of bandwidth. Estimated signal-to-noise ratio attributed to tape speed errors when recording FM signals is*

$$\frac{S}{N} = 20 \log \frac{D}{F}$$

where

D = deviation of information carrier in percent of carrier

F = flutter in peak-to-peak percent of tape speed at the highest information frequency

Net instantaneous error in percentage of bandwidth for an untranslated channel as a result of tape speed errors is given by:

$$\% \text{ error} = \frac{f_c \times F}{f_{bw}}$$

where

f_c = center frequency of the channel

F = flutter in peak percent

f_{bw} = bandwidth frequency of the channel

These figures become very critical as the deviation percentages become smaller or the tape speed errors become greater.

Compensating Circuits

When required, tape speed compensation circuits (TSC) are incorporated in the tape recorder motor circuit and/or in the multiplex/demultiplex electronics. TSC in the recorder motor circuit reduces long-term variation (low frequency flutter and jitter). Amplitude errors out of the FM detector due to flutter are reduced by TSC in the detector circuit.

While the method and type of compensation vary between the two, the basic operation is the same. A highly stable reference frequency is recorded along with the data, and variations caused by

TABLE I
REFERENCE FREQUENCIES SPECIFIED BY IRIG STANDARDS

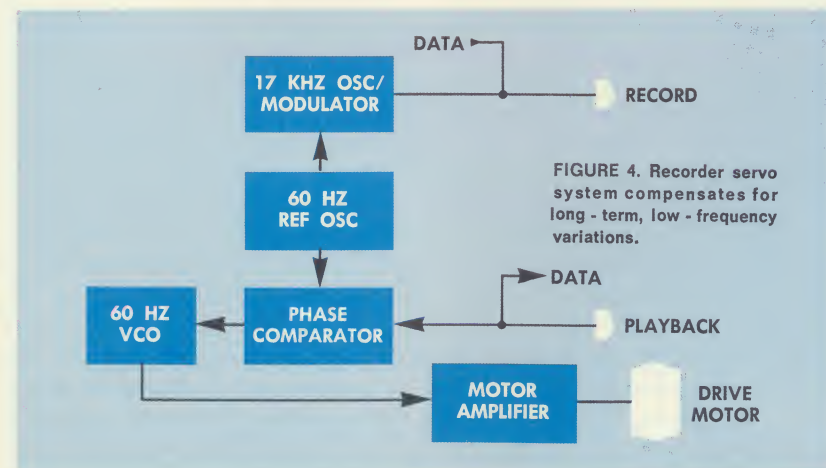
Reference Frequency (kHz)	Use
17.0	Use for servo-controlled recorder motor systems (delete channel 1A because of interaction).
25.0	Use for center frequencies up to and including 16 kHz.
50.0	Use for center frequencies up to and including 40 kHz except for channel C.
100.0	Use for center frequencies up to and including 80 kHz.
240.0	For use with all center frequencies.

the recorder affect the reference frequency the same as the data channels. The reference frequency is detected and any variations are used as error correction signals. The reference frequency can be multiplexed on the data or recorded alone on any track of a multiple-track tape.

IRIG Standards specify 7- and 14-track systems for analog and PDM recordings, and 16- and 31-track systems for PCM recordings. The disadvantage of the single-track reference is that the error may not be the same across all the tracks of a tape at any given instant causing skew. If this occurs, the error signal is not representative regardless of reference-track placement. However, the signal in

single-carrier (wideband, $\pm 40\%$ deviation) FM systems approaches a square wave (when using multi-vibrator type VCO's); thus, multiplexing the reference and data presents frequency problems, such as third harmonic resultants appearing in the data range, that necessitate using a separate track for the reference. When recorded on a separate track, any reference frequency channel may be chosen which has a wide enough frequency response.

The more practical approach is to multiplex the reference signal with the data. IRIG Standards specify that the reference frequencies listed in Table I be used when multiplexing the reference with the data.



* Stiltz, Harry L., *Aerospace Telemetry*, Prentice-Hall, Inc., June 1963, P. 352

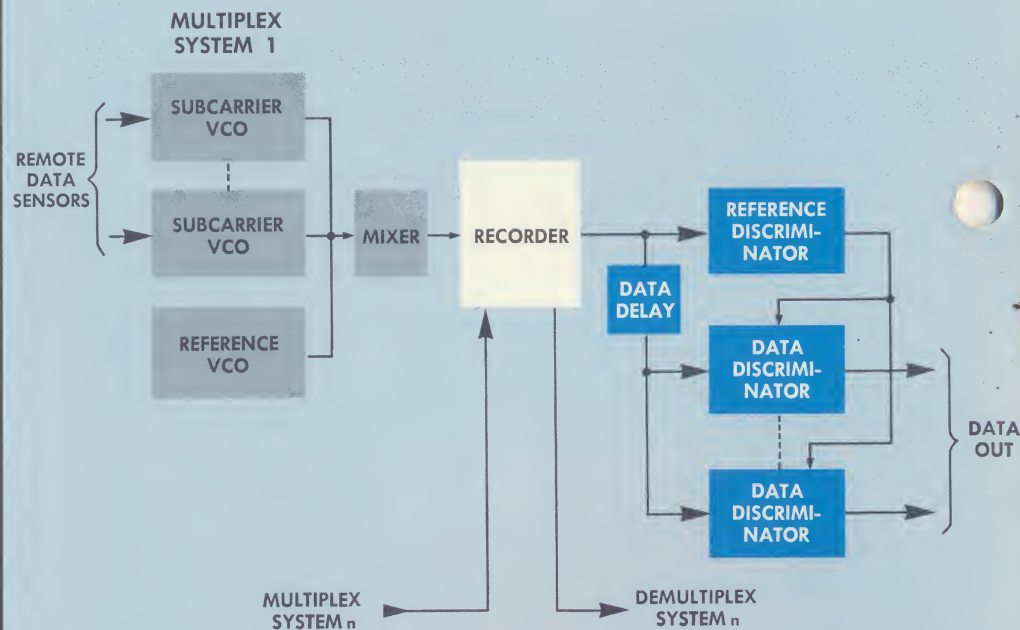


FIGURE 5. Speed variations (which appear as modulation) are detected from a demultiplexed reference signal and used to dynamically shift the operating point of the data discriminators and cancel the effects of the tape speed errors.

Long-term variation in tape velocity (very low frequency) caused by tape dimensional characteristics or line frequency variations can be compensated for by a recorder-motor servo system. A 17-kHz reference carrier is amplitude modulated by a 60-Hz standard frequency and multiplexed with the data subcarriers as shown in Figure 4. The playback 60-Hz signal is compared to the 60-Hz reference signal, and any error in frequency and phase is applied to a 60-Hz voltage-controlled oscillator (VCO). The output of the VCO controls the power source frequency for the recorder drive motor.

Dynamic Speed Errors

The tape speed compensation system shown in Figure 5 multiplexes a reference frequency chosen from Table 1 with the data signals, and the multiplexed signal (data and reference) is recorded on one track of a multiple-track tape recorder. Similar multiplexed signals could be recorded on the remainder of the tracks.

The output of the reference discriminator is an error signal with a polarity and magnitude representing the record and playback flutter which modulated the reference tone. The error signal is used

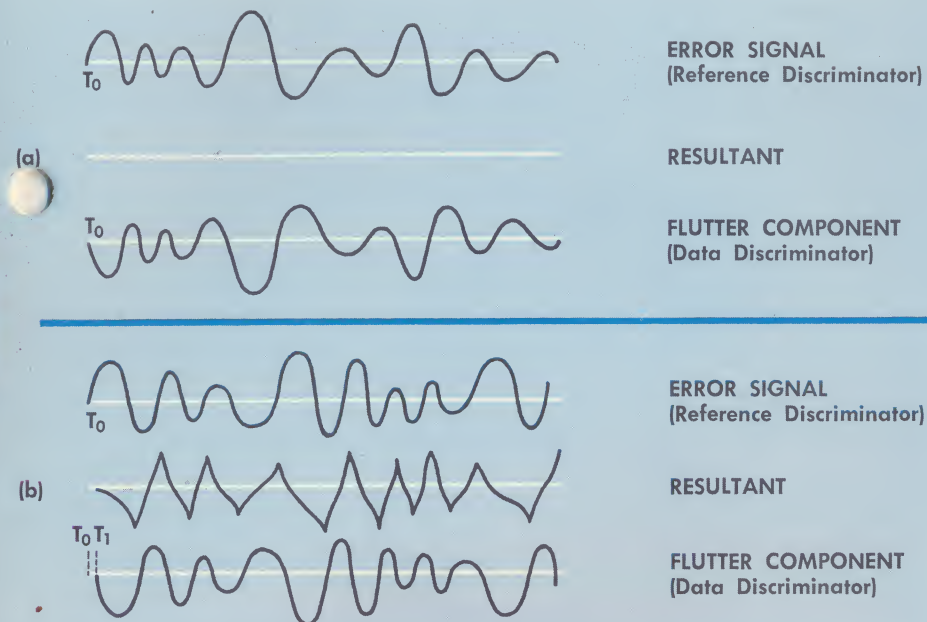


FIGURE 6. Maximum cancellation (a) is realized when reference error signal is of the correct phase and amplitude. Phase and/or amplitude differences introduce a resultant error into the system.

to instantaneously shift the bias level in the detector of each discriminator, thereby retuning the detector frequency. This TSC method of retuning the FM discriminator using the detected tape speed error as feedback control was originally developed by EMR.

The most critical aspect of the compensation system now becomes apparent. Maximum flutter cancellation cannot be realized if the error magnitude and time of occurrence do not correspond to the instantaneous flutter component detected by the data discriminator. Figure 6 is a simplified illustration of the cancellation process. Delay

is affected by all filter elements present in the signal paths, which includes the input and output filters in the discriminators. Figure 7 shows these delays and their relationship to each other.

The data delay, D3, is made equal to the reference discriminator delays D1 and D2 since D1 and D2 affect all the data channels the same amount. In addition, EMR reference discriminators incorporate a front-panel adjustment to vary the delay of D2 to provide exact matching which ensures that $D1 + D2 = D3$. This enables easy field adjustment if the data delay unit D3 is replaced or if compensation

for component value changes are necessary.

There is one other fixed delay to be considered and that is the delay (D4) of the bandpass input filter (BPIF) of each data discriminator. Each filter displays a nominal fixed delay which is inversely proportional to its center frequency and to bandedge deviation percentage. Therefore, each discriminator BPIF delay is different.

The delays in every signal path (D3 + D4) must equal the delays in the error compensation path. Since $D3 = D1 + D2$, an additional delay, D5, must be inserted to compensate for the different delays of D4 from channel to channel. EMR discriminators are manufactured

with this delay (D5) factory-adjusted within each channel selector.

The amplitude requirement for maximum flutter compensation is a function of the frequency response of each network and the frequency/voltage transfer functions of both the reference discriminator and the data discriminators, excluding the data discriminator output filter. Proper deviation sensitivities and polarity usually are automatically established internally if the same model discriminators are used throughout the system, or if the units used have identical characteristics. However, for best results, the manufacturer's recommendations concerning the discriminator setups should be followed.

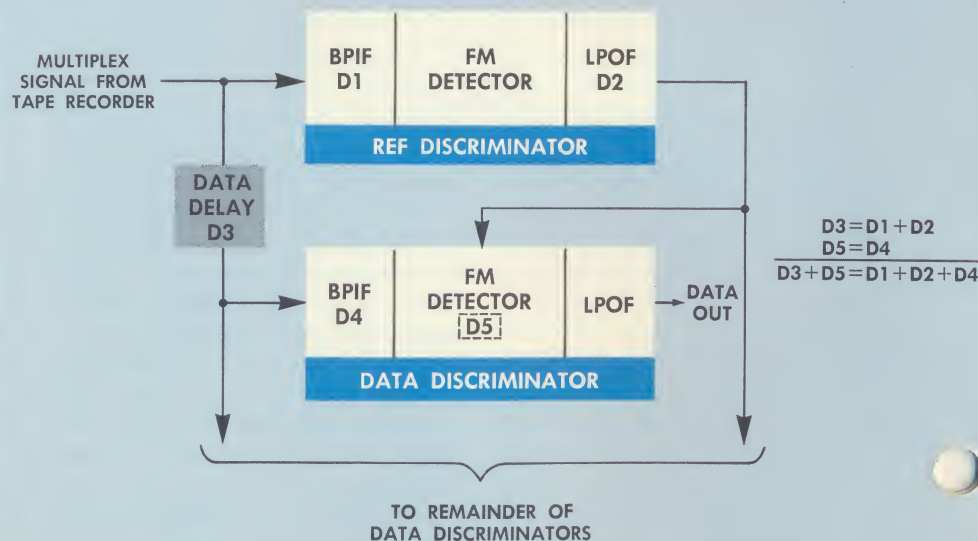


FIGURE 7. Fixed delays caused by filter elements in the reference discriminator must be offset to ensure maximum cancellation of the flutter component.

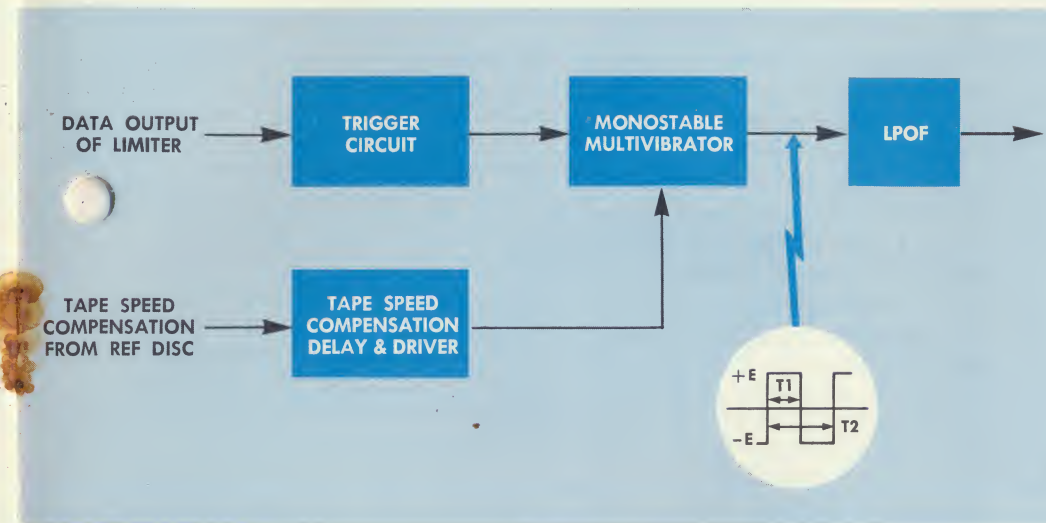


FIGURE 8. Pulse duration T1 is determined by the center frequency and repetition time T2 is determined by the modulating frequency. With no data input $T1 = \frac{1}{2}T2$ and the output is zero.

Types of Tape Speed Compensation

Two types of detectors used in FM discriminators are the pulse-averaging detector and the phase-locked-loop detector. The pulse-averaging detector consists of a trigger circuit, a monostable multivibrator, and a lowpass output filter (Figure 8). The trigger circuit shapes the output of the limiter to present a sharp rise time to the multivibrator which fires for each positive or negative excursion of the FM signal across some predetermined level. Multivibrator pulse duration is determined by the discriminator selected center frequency, with the repetition rate being a function of the FM input.

Pulse duration T1 is determined by the center frequency and repetition time T2 is determined by the modulating frequency. The tape

speed compensation driver retunes the multivibrator timing circuit so that flutter components cancel; i. e., under the condition when the carrier is not modulated by data, $T1 = \frac{1}{2}T2$, even in the presence of flutter.

The phase-locked-loop detector consists of a phase detector, an amplifier-filter, and a voltage-controlled oscillator (Figure 9). The output of the phase detector is proportional to the phase error between the incoming signal and the VCO. The phase detector output is amplified and applied to the VCO to tune the oscillator to the frequency of the FM data input. This reduces the phase error and consequently reduces the output of the phase detector. With such a phase-error loop, there is no frequency difference between the two inputs to the phase detector in a steady-

state condition when the VCO frequency is the same as the unmodulated channel subcarrier. Therefore, the data output will be proportional to the frequency deviation of the incoming signal except for dynamic errors.

The tape speed compensation signal from the reference discriminator dynamically varies the operating point of the VCO timing components (i.e., retunes the discriminator) to correspond to any tape speed errors. When all the delays and amplitudes have been properly set, the flutter components are eliminated and the phase-locked loop output will be representative of the input data signal.

The pulse-averaging detector (zero-crossing) and the phase-locked loop are two of several FM discriminator circuits. These two types are more widely used in telemetry applications because of

their numerous advantages including desirable broad-band linearity characteristics.

System Improvement

Theoretically, if the tape speed compensation signal had the correct amplitude and phase, the flutter error improvement would be infinite. Discussion up to this point has involved only the fixed delays which were offset by purposely inserting additional delays to balance the system. Now it is necessary to include the variation in delay of a signal as its frequency is changed across the passband. This effect is caused by the BPIF and must be considered when calculating the actual tape speed improvement figure.

Typical discriminator systems specify that a cycle of data will have a bandedge-to-bandedge shift

of $\pm 1^\circ$ for a deviation ratio of 5, and $\pm 2.5^\circ$ for a deviation ratio of 2. These figures apply to both the reference and data discriminators provided the subcarrier frequencies remain in the passband. The varying delay of delay line D3 is about half the BPIF delay D1, while delays D2 and D5 contribute negligible error. Therefore, in the worst case condition of D1, D3, and D4 differential delay could be as large as 5° for a deviation ratio of 2. This corresponds to a decrease in compensating ability of $\sin 5^\circ$, which is equal to 0.08, or 8%.

Therefore, the maximum improvement for a deviation ratio (DR) of 2 is:

$$20 \log \frac{E}{0.08E}$$

$$20 \log 12 = 22 \text{ db}$$

For a deviation ratio of 5, the differential delay is only 2° and

the maximum improvement is increased to:

$$20 \log \frac{E}{0.034E}$$

$$20 \log 30 = 30 \text{ db}$$

Usually, all tolerances do not combine in the worst case just described and typical improvement figures of 35 db and 25 db for deviation ratios of 5 and 2, respectively, are measurable. The relative contribution of each delay line and filter to the total error is highly dependent upon the specific system.

Figure 10 shows the expected improvement of a typical tape speed compensation system. These improvement figures are based on the assumption that the reference signal and data subcarriers are multiplexed and recorded on the same tape recorder track. If this were not the case, the improvement figure would be decreased because of skew.

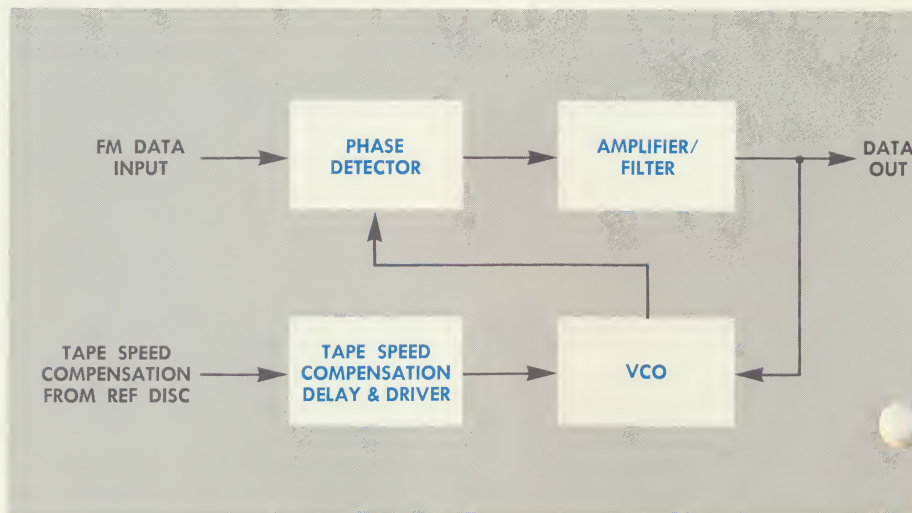


FIGURE 9. The VCO is tuned to the subcarrier frequency and any differences are detected in the phase detector. The TSC circuit is set for zero output from the phase detector with no data modulation input.

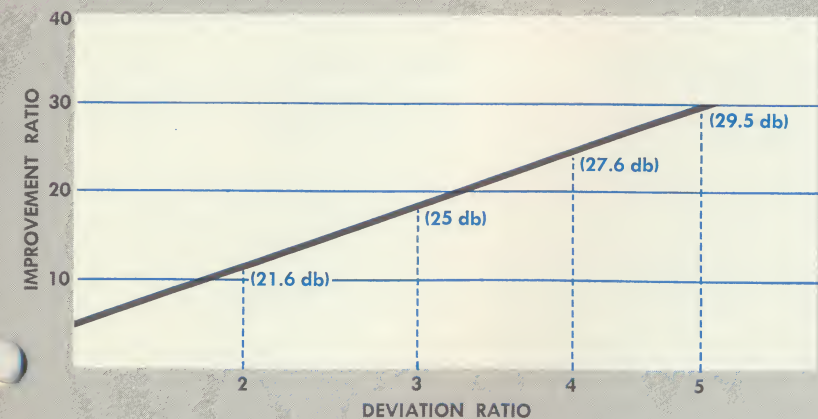


FIGURE 10. Improvement ratios calculated for TSC circuits increase as the deviation ratio increases. These figures are worst case conditions: considerably higher ratios have been measured. Corresponding db figures are shown in parentheses.

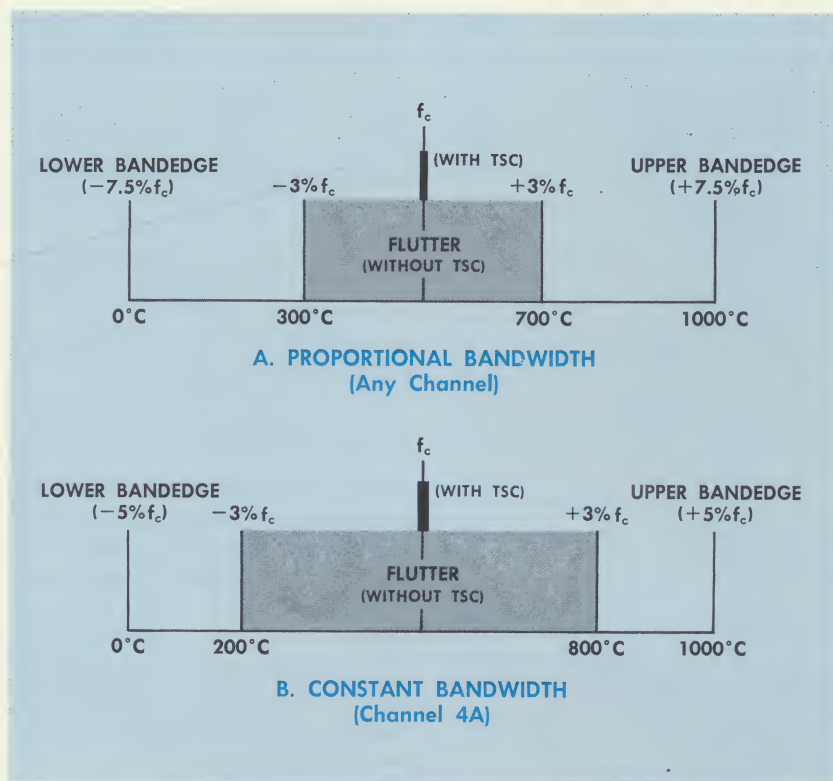


FIGURE 11. Flutter has a significant effect on both proportional bandwidth and constant bandwidth channels. Considerable improvements are realized in both cases when tape speed compensation circuits are used.

TSC in Typical Systems

Consider an FM system with a recorder having a flutter specification of 6% peak-to-peak with all channels operating at a DR of 5. One of the data points is a measurement of temperature ranging from 0°C to 1000°C. In a proportional-bandwidth system with standard deviations of $\pm 7.5\%$, the effect of the $\pm 3\%$ flutter is quite significant. The error as a fraction of bandwidth is $\pm \frac{0.03}{0.15}$ (or $\pm 20\%$), resulting in an error of $\pm 200^\circ\text{C}$ as

shown in Figure 11A. A TSC improvement of 30 db would reduce this error to 0.67% of bandwidth, or $\pm 6.7^\circ\text{C}$.

The percent bandwidth error in an FM system is inversely proportional to the percent deviation. In IRIG CBW channel 4A ($f_c = 40$ kHz, Dev. = ± 2 kHz), for example, the percent deviation is $\pm \frac{2 \text{ kHz}}{40 \text{ kHz}}$ or $\pm 5\%$. The error in percent of bandwidth is $\pm 100 \left(\frac{0.03}{0.10} \right)$ or $\pm 30\%$, resulting in an error of $\pm 300^\circ\text{C}$ as shown in Figure 11B.

A TSC improvement of 30 db would reduce this error to $\pm 1\%$ of bandwidth, or $\pm 10^\circ\text{C}$. In any channel above 7A ($f_c = 64$ kHz, Dev. = ± 2 kHz), the flutter percentage would exceed the percent deviation and therefore would exceed the designed bandwidth of the channel.

Adequate performance on constant bandwidth systems with low deviation percentage requires careful attention to filter design and manufacture. The use of translation/detranslation techniques overcomes the disadvantage of the poor signal-to-noise ratio of the channels due to flutter with high-frequency, low-percent deviation subcarriers. For example, IRIG Standards channel 21A has a center frequency of 176 kHz. With a deviation of ± 2 kHz, the percent deviation is:

$$\frac{2 \text{ kHz}}{176 \text{ kHz}} = 1.13\%.$$

If this channel is mixed during the recording process with a 200 kHz translation frequency in a system with a tape speed reference channel, the detranslated carrier would be 24 kHz. This results in a percent deviation of:

$$\frac{2 \text{ kHz}}{24 \text{ kHz}} = 8.34\%.$$

Recalling that the formula for an approximate S/N ratio due to flutter is

$$S/N = 20 \log \frac{\text{Deviation Percentage}}{\text{Flutter}}$$

it can be seen that a substantial improvement results with constant bandwidth frequency translation.

Tape speed compensation systems compensate for flutter as high as 10%. When required, these circuits can provide compensation for a high level of flutter allowing the engineer the wide flexibility needed in selecting equipment tradeoffs for today's varied applications. As a result, EMR discriminators are manufactured with built-in tape speed compensation capability to satisfy the most exacting system requirements.

Future Trends

Most tape recorder designs are a compromise between high-inertia capstan systems which reduce low-frequency variations and low-inertia systems which reduce high-frequency variations. Research is being conducted to further reduce speed variations by mounting the heads on electrodynamic transducers to move the heads longitudinally to correct for flutter up to 1000 Hz.

However, mechanical improvements for tape recorders have a practical limitation. A TSC system cannot improve the signal-to-noise ratio of the tape recorder, but when properly designed and adjusted, the TSC system can reduce the recorder flutter by more than 30 times. Future TSC systems will provide even greater flutter reductions with design improvements in the bandpass input filters. Perhaps the most significant advance will be the elimination of jitter, as well as flutter, with TSC systems using electrically variable delay lines.



TSC IN EMR'S NEWEST TUNABLE DISCRIMINATOR

The new EMR 4140 Tunable Discriminator is an ideal unit for those requiring tape-speed compensation over a wide range of frequencies and deviations. An optional TSC circuit in the 4140 includes an internal delay network that is automatically controlled by the center-frequency setting of the unit. You can be confident of high wow and flutter improvement even when you wish to cover the 4140's entire center frequency range of 100 Hz to 1.5 MHz. Combining this with data cutoff frequencies from 1 Hz to 300 kHz and any four subcarrier deviations from $\pm 7.5\%$ to $\pm 40\%$ makes the EMR 4140 the most versatile and useful tunable discriminator on the market.

For complete details on the EMR 4140, contact any EMR field office or write:

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The EMR Telemeter

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